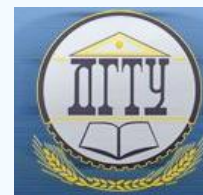


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Adaptation of structures of steel laser hardening zones to friction conditions

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Introduction. The structural state of the surface layers of engineering products manufactured through laser processing under various irradiation modes is considered. Structures with the highest possible stability with respect to external action under friction conditions, or with the possibility of optimal adjustment and additional hardening during operation by the formation of secondary structures, were implemented. Under the operating conditions, under the impact of mechanical and thermal pulses, an express rearrangement of one structure to another occurs, which is stable at a higher level of load-speed conditions. Thus, the phenomenon of structural-energy adaptability is realized. The resulting adaptable structures most efficiently dissipate the energy introduced into the tribosystem, and minimize the wear of friction pairs.

Materials and Methods. We studied samples of P6M5 steel using the following equipment:

- Kvant-16 processing station with a power density of 100 MW/m² for pulsed laser irradiation of samples;
- Neophot-21 optical microscope for metal physical studies;
- DRON-0.5 diffractometer for phase composition identification.

Results. It is established that the material of the samples after laser treatment is able to efficiently dissipate the energy supplied during friction through its transformations at various structural levels. As a result, it becomes possible to control the surface strength and wear resistance of materials using the concept of structural adaptability of friction pairs, which extends their range of performance. Wear resistance of the irradiated steels is determined by both their initial hardness and the work-hardenability during friction. It is established that the thermal-strength loading of the steel surface irradiated layers during friction destabilizes austenite to the $\gamma \rightarrow \alpha$ transformation, i.e., it contributes to its transformation into deformation martensite.

Discussion and Conclusions. In relation to the specific loading conditions, it is required to regulate the amount and degree of stability of the residual austenite in laser-hardened steels and alloys, which provides the necessary operational properties.

Keywords: laser irradiation, machine building materials, wear resistance, structural adjustability, surface strength

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Introduction. To increase the efficiency of hardening technologies including laser processing, it is necessary to determine the possibilities of targeted use of internal reserves of structural adaptability of products for various functional areas from steel and alloys under operating conditions [1–8]. It is required to analyze features of the structure-energy state of laser-irradiated materials in friction pairs and determine major directions for increasing the wear resistance of tribosystems.

Under laser processing, several ways of transforming the structure were used to goal-oriented changes in the properties of materials [9–12]:

- increasing the structure dispersion under local plastic deformation as a result of dynamic polygonization in austenite, the formation of microdomains (fragments) of high density dislocations inherited under accelerated cooling, and as a result of phase hardening during polymorphic transformation;
- formation of nanoscale extractions under the impact of plastic deformation under thermal exposure;
- development of deformation in irradiated zones of martensite under external temperature-force loading.

It should be taken into account that structural transformation, on the one hand, is a mechanism of strain hardening determined by an increase in the martensite volume, and, on the other hand, causes relaxation of microstresses and additional development of plastic deformation. These two factors act simultaneously and are competing [13–15]. In the case of the predominance of the first factor, high strength with satisfactory ductility is provided in steels. If the second factor dominates, the steel ductility increases significantly while maintaining a sufficient level of tensile strength.

With an optimal combination of factors, martensitic transformation under loading provides the best complex of mechanical properties of the material [16, 17].

Research Objective. Problems of designing adaptable alloy structures with specified operational characteristics using laser irradiation under optimal conditions were considered. The following ways were used to dissipate the energy pumped through laser processing and during the subsequent temperature-force tribological action:

- transformation of part of the energy into heat;
- dissipation due to the motion of defects in the crystal structure and plastic deformation;
- dissipation under structural-phase transformations at different scale levels.

The last structural factor is crucial for improving the operational properties of products if the structures formed under laser exposure are adaptable to operating conditions [18–19]. Adaptable martensitic-austenitic structures with a predetermined ratio of components that are purposefully formed under laser processing should efficiently dissipate energy in the friction zones due to internal transformations, especially when peak loads are reached. This is possible under laser irradiation under optimal conditions and is a prerequisite for increasing the reliability and durability of products.

The study objective was to obtain scientific knowledge on the possibility of implementation of structures in the laser processing zones of steels and alloys that adapt to temperature-force loading under friction and thereby increase the wear resistance of products.

Materials and Methods. Metal physical studies of samples from P6M5 instrument steel were carried out using a *Neophot-21* optical microscope, a DRON-0.5 diffractometer, and a PMT-3 durometer. Laser irradiation was carried out on a Kvant-16 pulsed-action facility with a radiation power density of 80–150 MW/m². Wear tests were carried out on the MI-1M installation according to the “disk — block” scheme at a load of 500 N with a linear sliding speed of 190 m/min. Samples in the form of disks went through a full cycle of volumetric heat treatment — they were quenched and triple-tempered. Some disks were irradiated along a side surface 10 mm wide. Inserts made of steel ShKh15 having hardness HB 130–180 served as counterfaces. Disk wear before and after laser irradiation was determined by weight loss through periodical weighing on an analytical balance with an accuracy of 10^{−4} g.

Research Results. Metallographic and durometric analyses of hardened samples have shown that after laser treatment, a hardened layer with a depth of 80–120 μm is formed on the surface. Fig. 1 shows the wear test results that demonstrate a distinct advantage of steels after surface laser treatment. Moreover, due to the running-in of friction pairs and structural changes on contacting surfaces with an increase in test time, the advantage increases by 13 times.

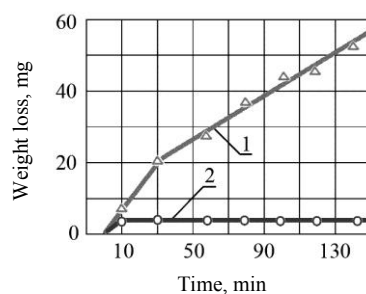


Fig. 1. Wear curves of samples from R6M5 steel after quenching at 1280°C and triple tempering (1), laser quenching (2)

Consider the features of structural and phase transformations realized in the surface layers of laser-hardened samples under friction and eventually causing an increase in the wear resistance of the material. X-ray diffraction studies of laser-irradiated samples of P6M5 steel were carried out before and after wear tests, for 15 minutes and 150 minutes. The results are presented in Fig. 2 in the form of fragments of X-ray patterns taken from the surfaces before and after friction.

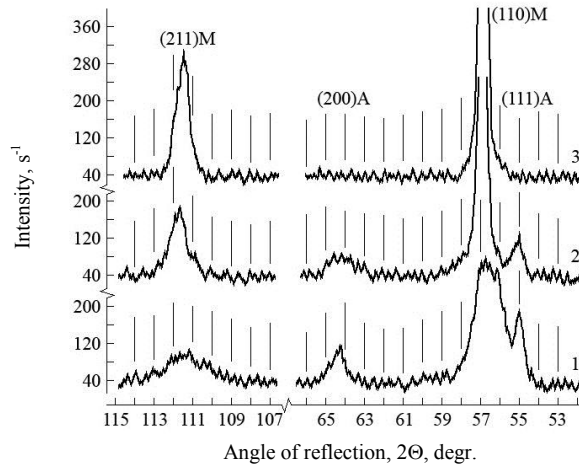


Fig. 2. Fragments of X-ray diagrams of R6M5 steel: 1 is after laser quenching; 2 is after laser quenching and wear tests for 15 min; 3 is after laser quenching and wear tests for 150 min.

Prior to wear tests, the surface layers of steel after laser hardening have a two-phase austenitic-martensitic structure (Fig. 2, curve 1). Moreover, the intensity of austenite reflections, and, consequently, its amount in the structure, decreases significantly with increasing the test time (Fig. 2, curves 2, 3). This is explained by the fact that the considered conditions of temperature-force loading destabilize austenite to martensitic transformation due to the precipitation of doped carbides from it. As a result of the γ -phase depletion by carbon, it acquires the ability to transform into martensite deformations with the properties similar to cooling martensite. This provides for technological and structural plasticity of the steel surface layers (micro TRIP effect).

It should be noted that martensite obtained through laser hardening, under the effect of temperatures and forces in the friction zones, also transforms due to strain hardening during wear (Fig. 2, curves 2, 3). Confirmation is the increase in the width of the martensite reflections in X-ray diffraction patterns caused by an increase in the density of dislocations and the refinement of the blocks of its fine structure. As a result, the hardness and performance of laser-irradiated steel is further enhanced. Thus, under friction, the structure of the irradiated surface layers adapts to the loading conditions in the friction pair, which leads to an increase in the hardness and wear resistance of steels after laser treatment.

Through changing the irradiation regime, a different amount of martensite and austenite was achieved in laser-hardened zones, and a connection between the development of phase transformations in the process of self-organization of structures and the properties of steels was established. The results of metal physical studies have shown that laser processing of P6M5 steel should be carried out with a power density in the range of 80–120 MW/m². In this case, the maximum possible hardening of steel is achieved at the level of 10–11.5 GPa, which causes an increase in the wear resistance of irradiated surfaces. An additional factor in increasing the wear resistance of steel under friction without lubrication is the preservation of insoluble carbides of tungsten, vanadium, chromium up to 30% in the laser processing zones.

It is established that under the action of high temperatures and pressures in the contact zones of the laser-irradiated metal, additional precipitation of carbides of the strengthening action occurs [20, 21]. This is facilitated by the high density of dislocations in steels both immediately after laser processing and additionally arising during friction.

Fig. 3 *a* shows the microstructure of irradiated P6M5 steel after the wear tests. A reference line is plotted; along it, a histogram of the surface profile height distribution, shown in Fig. 3 *b*, was determined. The line crosses the dispersed precipitated carbides. From the histogram, it follows that carbides have sizes in the range of 2–10 nm.

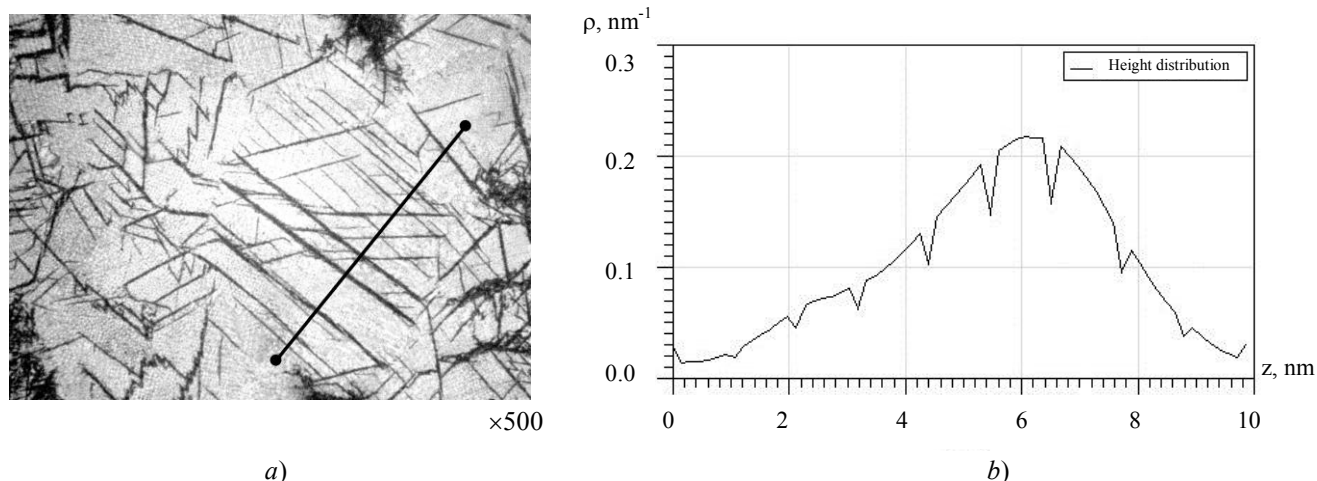


Fig. 3. Structure of laser-quenched R6M5 steel: *a*) optical microscopy results; *b*) histogram of surface profile height distribution

The precipitation of the dispersed carbide phase oriented along the sliding lines as a result of friction tests is noteworthy. The texture of dispersed precipitates thus formed causes a decrease in friction losses under the maintenance of products for various functional areas after laser treatment.

Discussion and Conclusions. We note the features of two-phase austenitic-martensitic zones of irradiated steels for different types of wear. The results considered in this paper were obtained under friction without lubrication. Under the abrasive wear, non-uniform structures of laser hardening have lower wear resistance compared to fully martensitic structures, which is explained by intensive wear of the austenitic structural component. Under the conditions of adhesive wear, as well as during the lubricated friction, two-phase structures of laser hardening zones are characterized by high wear resistance. In this case, the martensite sections play the role of a strong frame, and the wear-out austenite sections form microcavities on the working surface that hold the lubricant and improve the friction conditions.

Thus, to increase the wear resistance, it is required to design a structure adaptable to operating conditions with a certain ratio of the volumes of martensite, austenite and carbides by selecting the optimal laser processing mode. There are promising options for laser modification of the surface layers of steels with carbides or nitrides of doping elements, or laser quenching and subsequent tempering, the temperature of which depends on the steel grade.

Conclusions:

1. The possibilities of the purposeful use of internal reserves of structural adaptability of steels and alloys after laser surface treatment to improve their wear resistance under friction are determined.
2. The analysis of structural-phase transformations in the laser-irradiated zones of steels under temperature-force loading of friction pairs has been performed. It is shown that the transformation of residual laser hardened austenite into strain martensite, strain hardening of martensite obtained by laser heat treatment, and the multiple precipitations of dispersed reinforcing carbides in the irradiated zones of steels, contribute to increasing the wear resistance of materials.
3. Through changing the modes of laser treatment of steels, it is possible to form adaptable martensitic-austenitic structures in the irradiated zones with a given ratio of components that efficiently dissipate energy in the friction zones due to structural transformations at different levels.

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